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(54) **DOUBLE PATTERNING HARD MASK FOR DAMASCENE PERPENDICULAR MAGNETIC RECORDING (PMR) WRITER**

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CPC ***G11B 5/3116*** (2013.01); ***G11B 5/1278*** (2013.01); *G11B 5/3163* (2013.01); *Y10T 428/11* (2015.01)

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See application file for complete search history.

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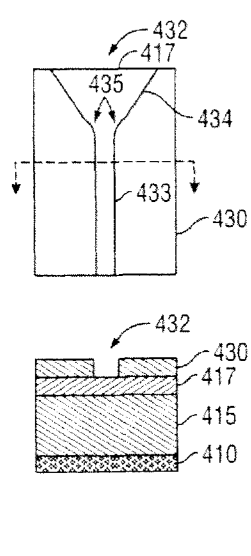
(57) **ABSTRACT**

Various embodiments of the subject disclosure provide a double patterning process that uses two patterning steps to produce a write structure having a nose shape with sharp corners. In one embodiment, a method for forming a write structure on a multi-layer structure comprising a substrate and an insulator layer on the substrate is provided. The method comprises forming a hard mask layer over the insulator layer, performing a first patterning process to form a pole and yoke opening in the hard mask layer, performing a second patterning process to remove rounded corners of the pole and yoke opening in the hard mask layer, removing a portion of the insulator layer corresponding to the pole and yoke opening in the hard mask layer to form a trench in the insulator layer, and filling the trench with a magnetic material.

7 Claims, 10 Drawing Sheets



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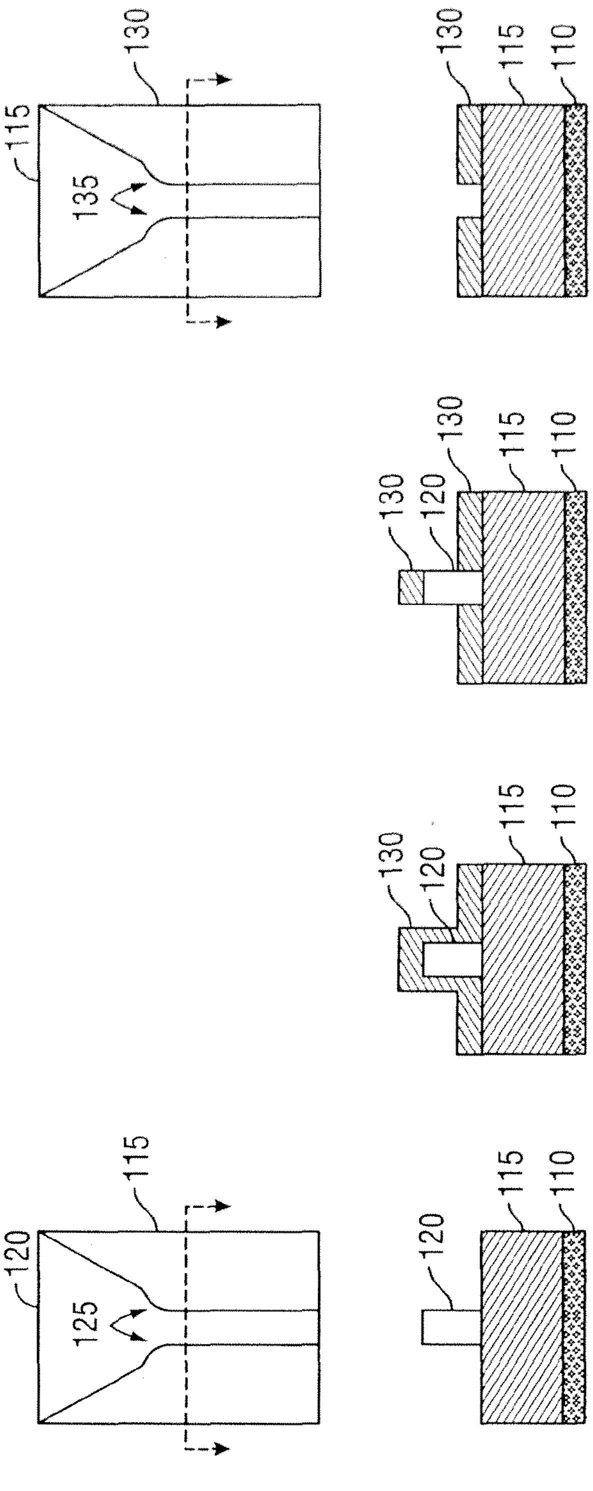

FIG. 1A
(Prior Art)

FIG. 1B
(Prior Art)

FIG. 1C
(Prior Art)

FIG. 1D
(Prior Art)

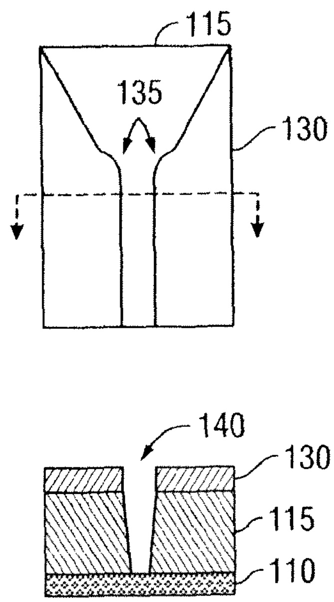

FIG. 1E
(Prior Art)

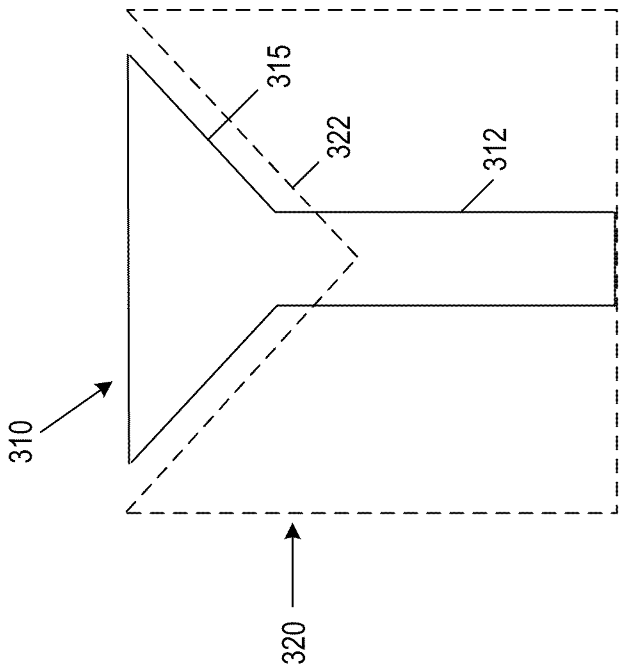

Fig. 3

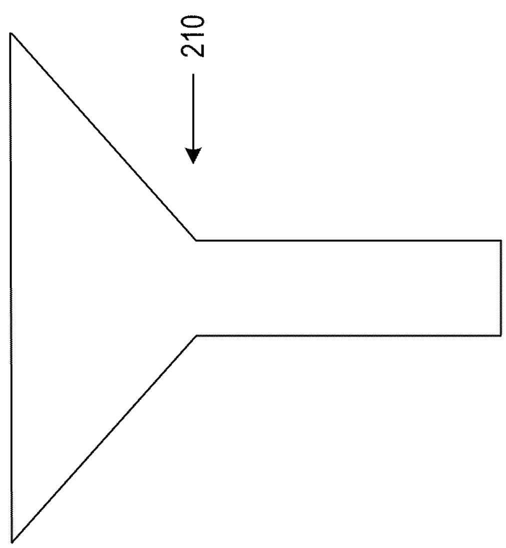

Fig. 2
(Prior Art)

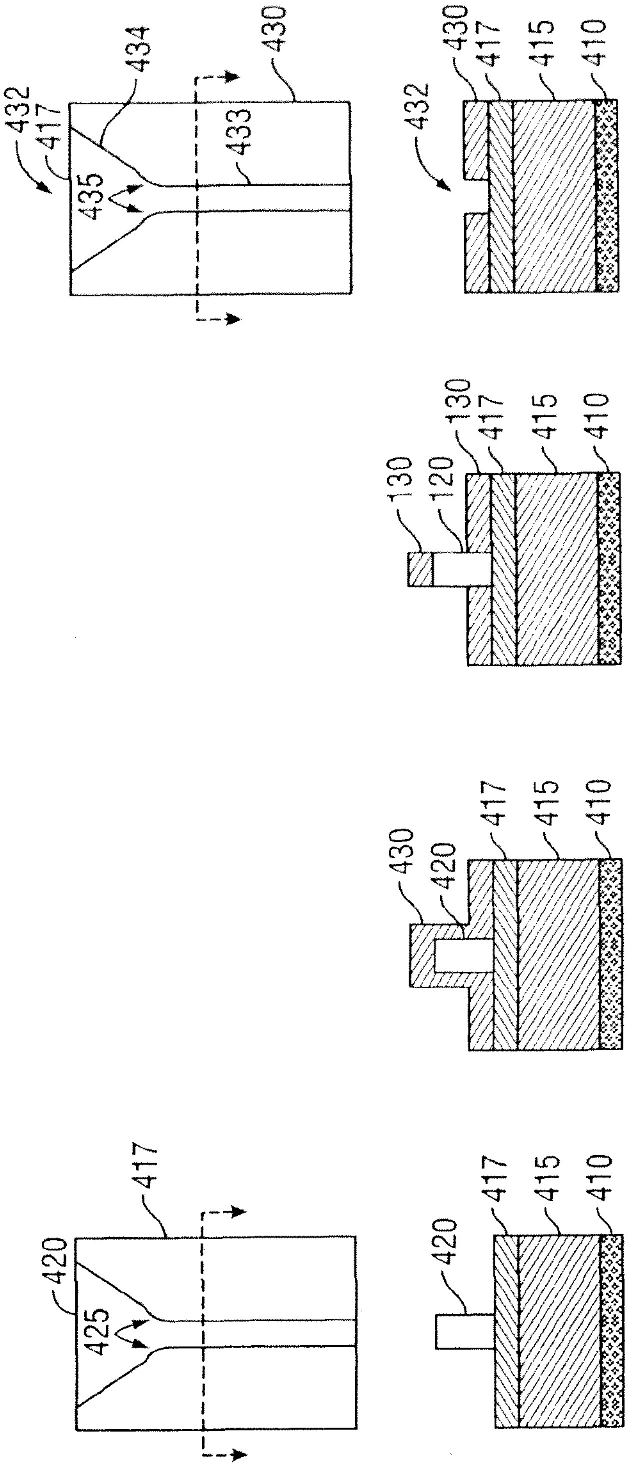

FIG. 4D

FIG. 4C

FIG. 4B

FIG. 4A

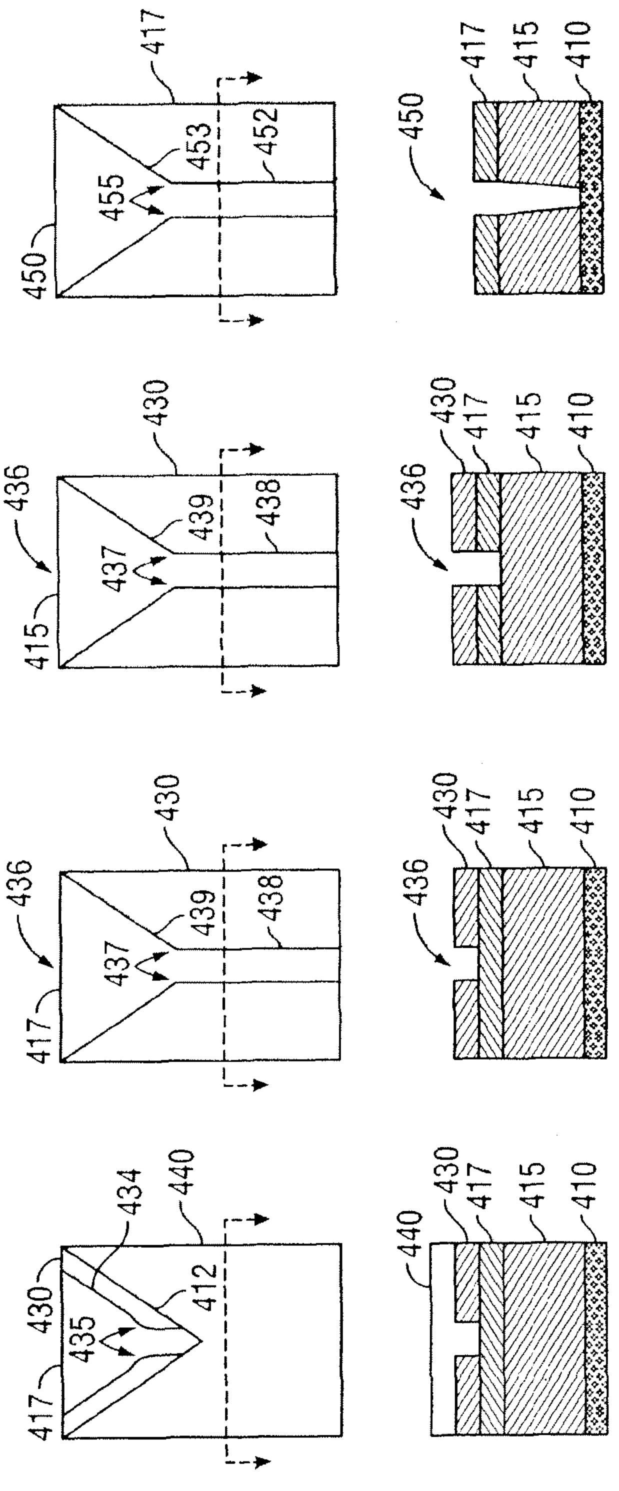

FIG. 4H

FIG. 4G

FIG. 4F

FIG. 4E

610

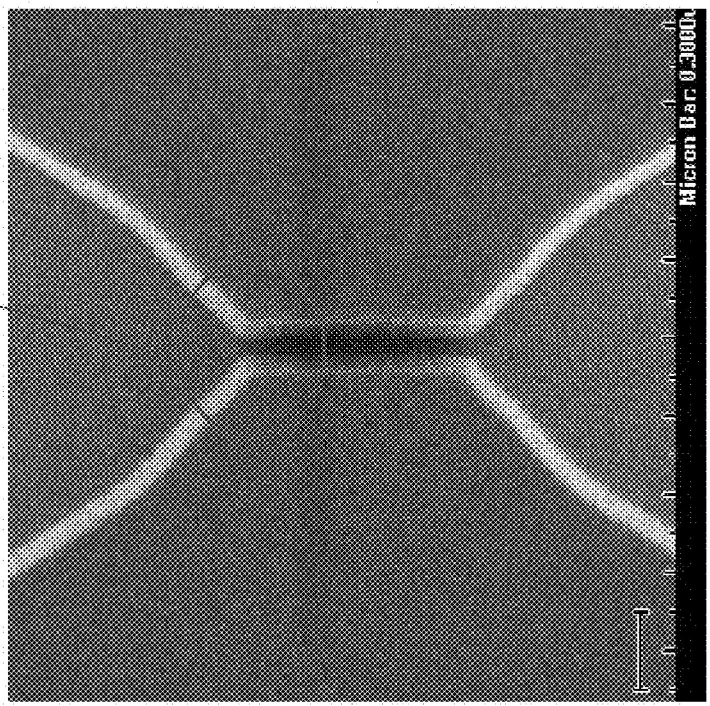

Fig. 6

510

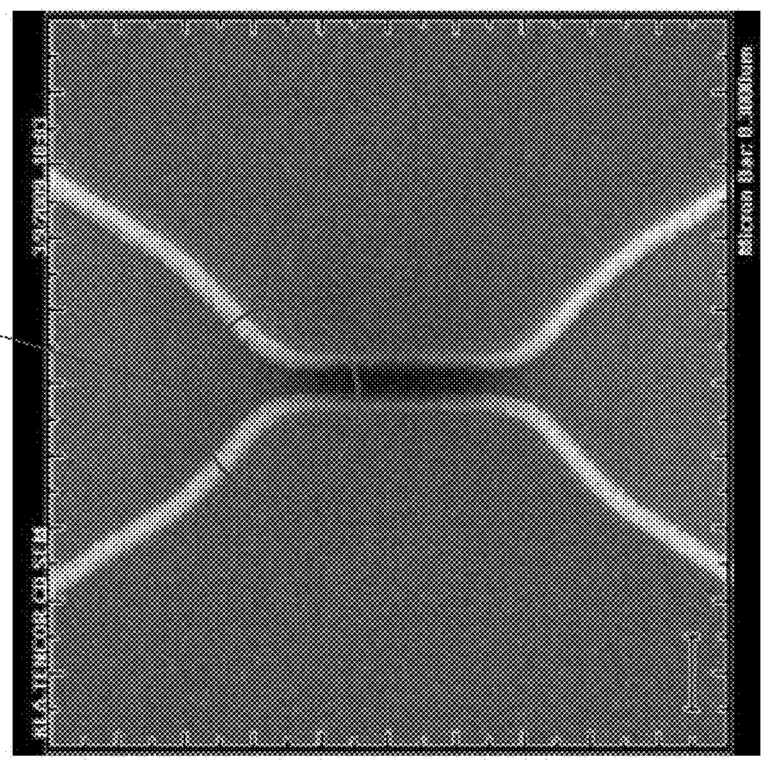

Fig. 5

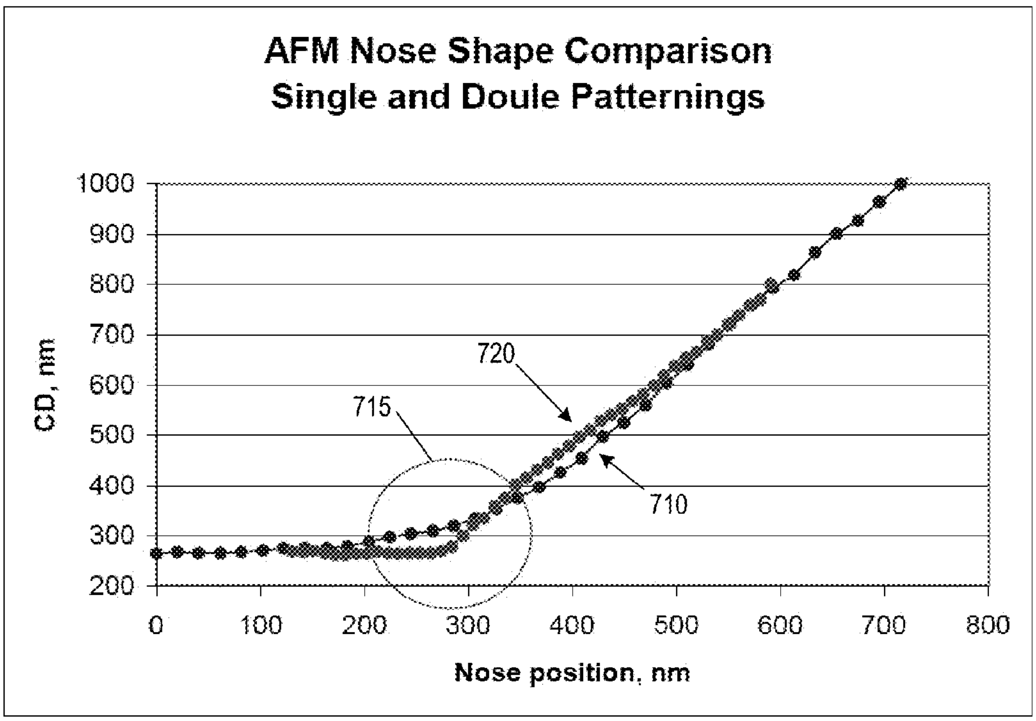
AFM Nose Shape Comparison
Single and Doule Patternings
1000
900
800
700
600
500
400
300
200
CD, nm
0
100
200
300
400
500
600
700
800
Nose position, nm
720
715
710

Fig. 7

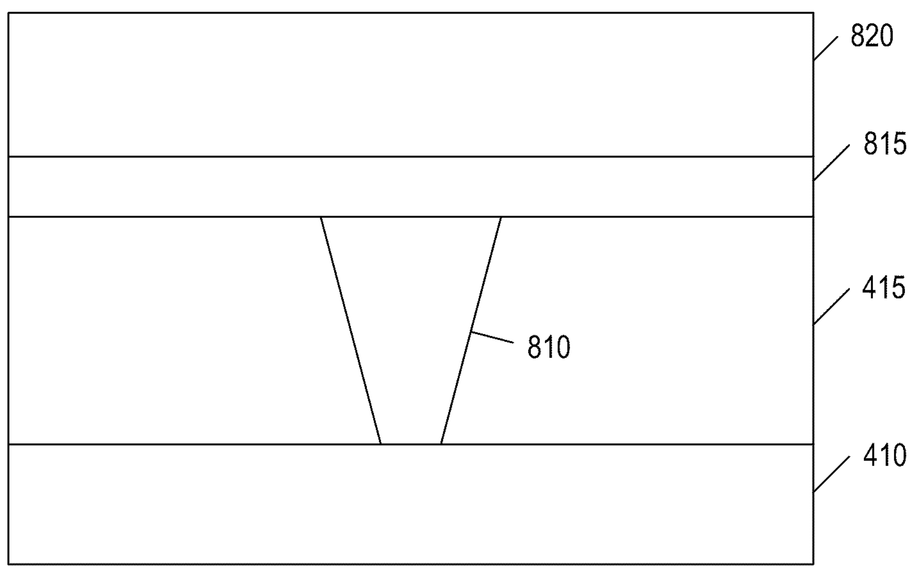

Fig. 8

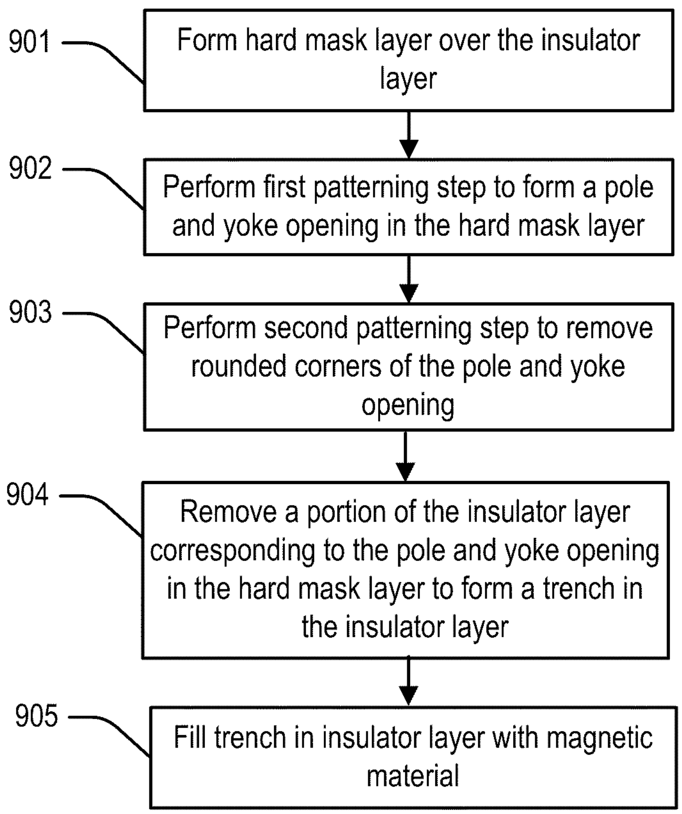
901
Form hard mask layer over the insulator layer
902
Perform first patterning step to form a pole and yoke opening in the hard mask layer
903
Perform second patterning step to remove rounded corners of the pole and yoke opening
904
Remove a portion of the insulator layer corresponding to the pole and yoke opening in the hard mask layer to form a trench in the insulator layer
905
Fill trench in insulator layer with magnetic material

Fig. 9

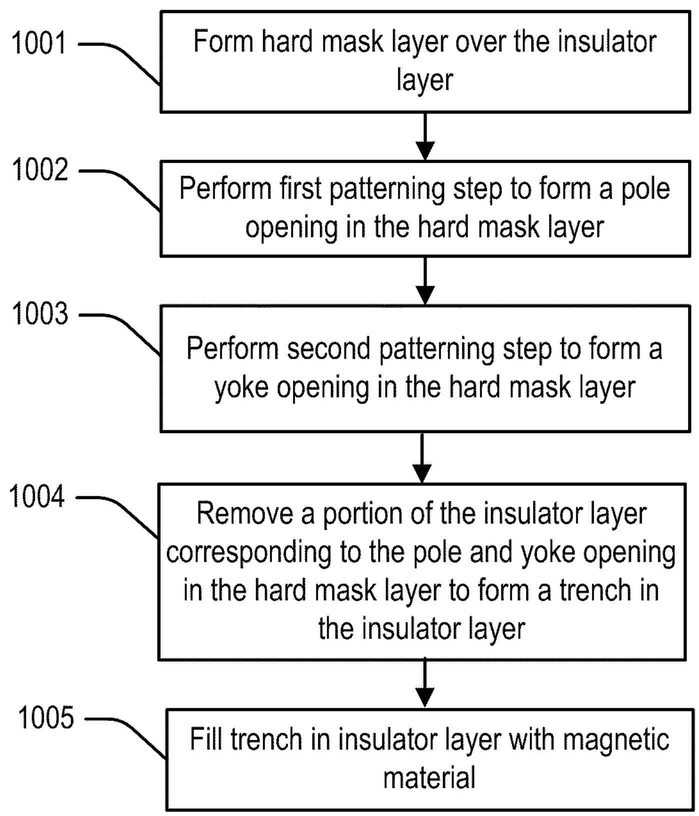
1001
Form hard mask layer over the insulator layer
1002
Perform first patterning step to form a pole opening in the hard mask layer
1003
Perform second patterning step to form a yoke opening in the hard mask layer
1004
Remove a portion of the insulator layer corresponding to the pole and yoke opening in the hard mask layer to form a trench in the insulator layer
1005
Fill trench in insulator layer with magnetic material

Fig. 10

DOUBLE PATTERNING HARD MASK FOR DAMASCENE PERPENDICULAR MAGNETIC RECORDING (PMR) WRITER

FIELD OF THE INVENTION

The present invention generally relates to hard disk drives and, in particular, relates to fabrication of perpendicular magnetic recording (PMR) writers.

BACKGROUND OF THE INVENTION

Magnetic disk drives are used to store and retrieve data for digital electronic apparatuses such as computers. One example of a disk drive is a hard disk drive. A conventional hard disk drive includes a rotating magnetic disk, write and read heads that are suspended by a suspension arm adjacent to a surface of the rotating magnetic disk, and an actuator that swings the suspension arm to place the read and write heads over selected circular tracks on the rotating disk. The read and write heads are directly located on a slider that has an air bearing surface (ABS). The suspension arm biases the slider towards the surface of the disk, and when the disk rotates, air adjacent to the disk moves along with the surface of the disk. The slider flies over the surface of the disk on a cushion of the moving air.

When the slider rides on the air bearing, the write and read heads are employed for writing magnetic transitions to and reading magnetic transitions from the rotating disk. The read and write heads are connected to processing circuitry that operates according to a program to implement writing and reading functions.

Perpendicular magnetic recording (PMR) writers are now being utilized in write heads to increase the data density of hard disk drives. Such PMR writers record magnetic bits of data in a direction that is perpendicular to the surface of the magnetic disk. A PMR writer generally includes a write pole having a relatively small cross sectional surface at the air bearing surface (ABS) and a return pole having a larger cross sectional surface at the ABS. A magnetic write coil induces a magnetic flux to be emitted from the write pole in a direction generally perpendicular to the plane of the magnetic disk.

Traditionally, a PMR write pole is defined and fabricated using one-step photolithography and a subsequent reactive ion etch or ion-mill. FIGS. **1A**-**1E** show a conventional PMR fabrication process using one-step photolithography.

FIG. **1A** shows a top view and a cross-sectional view of a multi-layer structure comprising a substrate **110**, an insulator layer **115** and a photoresist layer **120**. The photoresist layer **120** is patterned to form a nose pattern in the photoresist layer **120** using one-step photolithography with one photo mask **210** (shown in FIG. **2A**). The nose pattern comprises a pole pattern and a yoke pattern that tapers downward to the pole pattern. Due to the optical proximity effect, the corners **125** of the nose pattern are rounded, as shown in the top view in FIG. **1A**.

In FIG. **1B**, a ruthenium (Ru) layer **130** is deposited over the photoresist layer **120**. In FIG. **1C**, the Ru layer **130** on the sides of the photoresist layer **120** is removed using side milling. In FIG. **1D**, the photoresist layer **120** and the Ru **130** layer on the top of the photoresist layer **120** are lifted off to transfer the nose pattern from the photoresist layer **120** to the Ru layer **130**. As shown in the top view in FIG. **1D**, the nose pattern transferred to the Ru layer **130** includes rounded corners **135** corresponding to the rounded corners **125** in the photoresist layer **120**.

In FIG. **1E**, the patterned layer Ru **130** is used as a hard mask for a reactive ion etch (RIE) to form a trench **140** in the insulator layer **115**. The trench **140** includes a yoke trench and a pole trench. In a subsequent step, the trench **140** in the insulator layer **115** is filled with a magnetic material (not shown). The magnetic material in the pole trench forms a write pole.

In a later process, a portion of the write pole is lapped off to form a cross sectional surface at the ABS that faces the magnetic disk and though which magnetic flux flows from the write pole to the magnetic disk for writing data to the magnetic disk. The write pole is lapped along a plane that is perpendicular to the top view in FIG. **1E**.

New generation PMR writers require very short nose lengths with no nose shape rounding and zero chisel angle at ABS to ensure high write performance and to reduce variations in write performance from device to device. Conventional PMR fabrication processes are unable to meet this require because of nose shape rounding due to the optical proximity effect.

SUMMARY OF THE INVENTION

Various embodiments of the subject disclosure solve the foregoing problems by providing a double patterning process that uses two patterning steps to produce a nose shape with sharp corners.

According to one embodiment of the subject disclosure, a method for forming a write structure on a multi-layer structure comprising a substrate and an insulator layer on the substrate is provided. The method comprises forming a hard mask layer over the insulator layer, performing a first patterning process to form a pole and yoke opening in the hard mask layer, performing a second patterning process to remove rounded corners of the pole and yoke opening in the hard mask layer, removing a portion of the insulator layer corresponding to the pole and yoke opening in the hard mask layer to form a trench in the insulator layer, and filling the trench with a magnetic material.

According to another embodiment of the subject disclosure, a method for forming a write structure on a multi-layer structure comprising a substrate and an insulator layer on the substrate is provided. The method comprises forming a hard mask layer over the insulator layer, performing a first patterning process to form a pole opening in the hard mask layer, performing a second patterning process to form a yoke opening in the hard mask layer, the yoke opening overlapping the pole opening, removing a portion of the insulator layer corresponding to the pole opening and the yoke opening in the hard mask layer to form a trench in the insulator layer, and filling the trench with a magnetic material.

It is to be understood that both the foregoing summary of the invention and the following detailed description are exemplary and explanatory and are intended to provide further explanation of the invention as claimed.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings, which are included to provide further understanding of the invention and are incorporated in and constitute a part of this specification, illustrate embodiments of the invention and together with the description serve to explain the principles of the invention. In the drawings:

FIG. **1A**-**1E** illustrate a conventional PMR fabrication process;

FIG. 2 illustrates a photo mask used in one-step photolithography in the conventional PMR fabrication process;

FIG. 3 illustrates two photo masks used in a double patterning PMR fabrication process according to an aspect of the subject disclosure;

FIGS. 4A-4H illustrate a double patterning PMR fabrication process according to an aspect of the subject disclosure;

FIG. 5 shows a top-down critical dimension scanning electron microscope (CDSEM) image of a nose shape after trench formation for a conventional PMR fabrication process;

FIG. 6 shows a top-down CDSEM image of a nose shape after trench formation for a double patterning PMR fabrication process according to an aspect of the subject disclosure;

FIG. 7 shows nose shape comparisons between a convention PMR fabrication process and a double patterning PMR fabrication process according to an aspect of the subject disclosure;

FIG. 8 illustrates a portion of a write head as viewed toward the ABS according to an aspect of the subject disclosure;

FIG. 9 is a flow chart illustrating a double patterning method for forming a write structure according to an aspect of the subject disclosure; and

FIG. 10 is a flow chart illustrating a double patterning method for forming a write structure according to another aspect of the subject disclosure.

DETAILED DESCRIPTION OF THE INVENTION

In the following detailed description, numerous specific details are set forth to provide a full understanding of the present invention. It will be apparent, however, to one ordinarily skilled in the art that the present invention may be practiced without some of these specific details. In other instances, well-known structures and techniques have not been shown in detail to avoid unnecessarily obscuring the present invention.

FIGS. 4A-4H show a double patterning PMR fabrication process for fabricating a write pole according to an aspect of the subject disclosure. The double patterning process uses two photolithography steps with two photo masks to produce a nose shape with sharp corners.

FIG. 4A shows a top view and a cross-sectional view of a multi-layer structure comprising a substrate **410**, an insulator layer **415**, a first hard mask layer **417**, and a first photoresist layer **420**. The insulator layer **415** may comprise alumina or other magnetically insulating material. The first hard mask layer **417** may comprise ruthenium (Ru).

The first photoresist layer **420** is patterned using a first photolithography step to form a pole and yoke pattern in the first photoresist layer **420**. The first photolithography step uses a first photo mask **310** (shown in FIG. 3) to define the pole and yoke pattern. The pole and yoke pattern comprises a pole pattern **312** and a yoke pattern **315** that tapers downward to the pole pattern **312**. The pole and yoke pattern in the first photo mask **310** is transferred from the first photo mask **310** to the photoresist layer **420** during the first photolithography step. However, due to the optical proximity effect, the corners **425** of the yoke and pole pattern in the photoresist layer **420** may be rounded instead of sharp, as shown in the top view in FIG. 4A.

In FIG. 4B, a second hard mask layer **430** is deposited over the first photoresist layer **420** and the first hard mask layer **417**. The second hard mask layer **430** may comprise tantalum (Ta). In FIG. 4C, the second hard mask layer **430** on the sides of the first photoresist layer **420** is removed using side milling. In FIG. 1D, the first photoresist layer **420** and the second hard mask layer **430** on the top of the first photoresist layer **420** are lifted off to transfer the pole and yoke pattern from the first photoresist layer **420** to the second hard mask layer **430**. This forms a corresponding pole and yoke opening **432** in the second hard mask layer **430**. The pole and yoke opening **432** includes a pole opening **433** and a yoke opening **434**. As shown in the top view in FIG. 1D, the pole and yoke opening **432** may include rounded corners **435** corresponding to the rounded corners **425** in the first photoresist layer **420**.

In FIG. 4E, a second photoresist layer **440** is deposited over the second hard mask layer **430** and the insulator layer **415**. The second photoresist layer **440** is patterned using a second photolithography step to form a pattern that exposes the rounded corners **435** of the yoke and pole opening **432** in the second hard mask layer **430** and includes a yoke pattern **442** below the yoke opening **434** in the second hard mask layer **430**, as shown in the top view in FIG. 4E. The second photolithography step uses a second photo mask **320** (shown with dashed lines in FIG. 3) to define the pattern in the second photoresist layer **440**.

FIG. 3 shows both the first and second photo masks **310** and **320** including the relative position of the second photo mask **320** to the first photo mask **310**. In FIG. 3, the outline of the second photo mask **320** is dashed to show the overlap between the first and second photo masks **310** and **320**. The second photo mask **320** includes a yoke pattern **322** below the yoke pattern **315** of the first photo mask **310**.

In FIG. 4F, the portion of the second hard mask layer **430** exposed by the second photoresist layer **440**, which includes the rounded corners **435**, is removed by a RIE. The second photoresist layer **440** is then stripped away. The RIE etches away the rounded corners **435** in the second hard mask layer **430** and transfers the yoke pattern **442** in the second photoresist layer **440** to the second hard mask layer **430**. This results in a pole and yoke opening **436** with sharp corners **437** in the second hard mask layer **430**, as shown in the top view in FIG. 4F. The pole and yoke opening **436** in the second hard mask layer **430** comprises a pole opening **438** defined by the first photolithography step using the first photo mask **310** and a yoke opening **439** defined by the second photolithography step using the second photo mask **320**.

In FIG. 4G, the first hard mask layer **417** is etched with a RIE using the second hard mask layer **430** as a hard mask for the RIE. During the RIE, a portion of the first hard mask layer **417** exposed by the pole and yoke opening **436** in the second hard mask layer **430** is removed, transferring the pole and yoke opening **436** from the second hard mask layer **430** to the first hard mask layer **417**.

In FIG. 4H, the insulator layer **415** is etched with an insulator RIE using the first hard mask layer **417** as a hard mask for the insulator RIE. During the insulator RIE, a portion of the insulator layer **415** exposed by the pole and yoke opening in the first hard mask layer **417** is removed. This forms a trench **450** in the insulator layer **115** having a nose shape with sharp corners **455**. The trench **450** includes a pole trench **452** and a yoke trench **453**. The insulator RIE also etches away the second hard mask layer **430**. In a subsequent step, the trench **450** in the insulator layer **415** is filled with a magnetic material (not shown). The magnetic material in the pole trench **452** forms a write pole, and the magnetic material in the yoke trench **453** forms a write yoke that concentrates magnetic flux induced by magnetic write coils into the write pole.

In a later process, a portion of the write pole is lapped off to form an cross sectional surface ABS that faces the magnetic disk and though which magnetic flux flows from the write pole to the magnetic disk for writing data to the magnetic disk. The write pole is lapped along a plane that is perpendicular to the top view in FIG. **4**H to form the cross sectional surface.

Thus, the double patterning PMR fabrication process results in sharp nose corners with substantially no rounding and zero chisel angle at ABS. The double pattering PMR fabrication substantially eliminates the nose corner rounding associated with conventional PMR fabrication processes.

FIG. **5** shows a top-down critical dimension scanning electron microscope (CDSEM) image of the nose shape after RIE trench formation for a conventional PMR fabrication process using one photolithography step. FIG. **6** shows a top-down CDSEM image of the nose shape after RIE trench formation for the double patterning PMR fabrication process. As shown in FIG. **5**, the conventional PMR fabrication process results in a nose shape having rounded corners **510**. In contrast, as shown in FIG. **6**, the double patterning PMR fabrication results in a nose shape having sharp corners **610**. Thus, the image in FIG. **6** demonstrates that the double patterning PMR fabrication process substantially eliminates nose corner rounding.

FIG. **7** shows dimensions of a nose shape **710** for the convention fabrication process measured using atomic force microscope (AFM) metrology after trench formation. The measured nose shape **710** for the conventional fabrication process shows nose corner rounding in region **715** with no sharp transition between the yoke and the pole. FIG. **7** also shows dimensions of a nose shape **720** for the double patterning fabrication process measured using AFM metrology after trench formation. The measured nose shape **720** for the double patterning fabrication process shows a sharp corner in region **715**, which provides a sharp transition between the yoke and the pole.

The nose corner rounding resulting from the conventional fabrication process causes variations in the width of the pole along the length of the pole. This can be seen in FIG. **7**, where the width of the pole varies along the length of the pole, which extends from the left of the nose corner located at approximately 280 nm in FIG. **7**. As a result of the pole width variation, the shape of the cross sectional surface of the write pole at the ABS is highly dependent on the position at which the write pole is lapped. In the example in FIG. **7**, the shape of the cross sectional surface of the write pole is highly dependent on lapping position within a range of approximately 100 nm from the nose corner. Variations in lapping position among different write poles causes variations in the shape of their cross sectional surfaces, which in turn leads to variations in write performance among the write poles.

In contrast, the nose shape **720** resulting from the double patterning fabrication process exhibits a sharp corner that provides a sharp transition between the yoke and the pole. As a result, the pole is relatively straight along the length of the pole, which extends from the left of the nose corner located at approximately 280 nm in the example in FIG. **7**. Because the pole is relatively straight, the width, and hence the shape of the cross sectional surface of the write pole, is much less dependent on lapping position. The significantly reduced dependence on lapping position, leads to much greater uniformity in the shape of the cross sectional surfaces and write performances among write poles.

FIG. **8** illustrates a portion of a write head as viewed toward the ABS that may be formed by the double patterning PMR fabrication process. The write head may include the substrate **410**, the insulator layer **415** (e.g., alumina), a write pole **810**, a write gap **815** and a top shield **820**. FIG. **8** shows the cross sectional surface of the write pole **810** that faces the magnetic disk. As discussed above, the cross sectional surface of the write pole **810** is defined by lapping the write pole at a distance from the nose corner along a plane perpendicular to the top view shown in FIG. **4**H. To write data to the magnetic disk, magnetic flux is emitted from the cross sectional surface of the write pole **810** in a direction generally perpendicular to the cross sectional surface of the write pole **810** and the surface of the magnetic disk.

FIG. **9** illustrates a method for forming a write structure on a multi-layer structure comprising a substrate and an insulator layer on the substrate according to an aspect of the subject disclosure. The insulator layer may comprise alumina or other magnetically insulating material.

In step **901**, a hard mask layer is formed over the insulator layer. The hard mask layer may comprise ruthenium (Ru), tantalum (Ta) or other material. In step **902**, a first patterning process is performed to form a pole and yoke opening in the hard mask layer. Due to the optical proximity effect, the pole and yoke opening of the hard mask layer may have rounded corners. In step **903**, a second patterning process is performed to remove the rounded corners of the pole and yoke opening in the hard mask layer. In step **904**, a portion of the insulator layer corresponding to the pole and yoke opening in the hard mask layer is removed to form a trench in the insulator layer. In step **905**, the trench in the insulator layer is filled with a magnetic material.

FIG. **10** illustrates a method for forming a write structure on a multi-layer structure comprising a substrate and an insulator layer on the substrate according to an aspect of the subject disclosure.

In step **1001**, a hard mask layer is formed over the insulator layer. The hard mask layer may comprise ruthenium (Ru), tantalum (Ta) or other material. In step **1002**, a first patterning process is performed to form a pole opening in the hard mask layer. In step **1003**, a second patterning process is performed to form a yoke opening in the hard mask layer, the yoke opening overlapping the pole opening. In step **1004**, a portion of the insulator layer corresponding to the pole opening and the yoke opening in the hard mask layer is removed to form a trench in the insulator layer. In step **1005**, the trench in the insulator layer is filled with a magnetic material.

The description of the invention is provided to enable any person skilled in the art to practice the various embodiments described herein. While the present invention has been particularly described with reference to the various figures and embodiments, it should be understood that these are for illustration purposes only and should not be taken as limiting the scope of the invention.

There may be many other ways to implement the invention. Various functions and elements described herein may be partitioned differently from those shown without departing from the spirit and scope of the invention. Various modifications to these embodiments will be readily apparent to those skilled in the art, and generic principles defined herein may be applied to other embodiments. Thus, many changes and modifications may be made to the invention, by one having ordinary skill in the art, without departing from the spirit and scope of the invention.

A reference to an element in the singular is not intended to mean "one and only one" unless specifically stated, but rather "one or more." The term "some" refers to one or more. Underlined and/or italicized headings and subheadings are used for convenience only, do not limit the invention, and are not referred to in connection with the interpretation of the description of the invention. All structural and functional equivalents to the elements of the various embodiments of the invention described throughout this disclosure that are known or later come to be known to those of ordinary skill in the art are expressly incorporated herein by reference and intended to be encompassed by the invention. Moreover, nothing disclosed herein is intended to be dedicated to the public regardless of whether such disclosure is explicitly recited in the above description.

What is claimed is:

1. A method for forming a write structure on a multi-layer structure comprising a substrate and an insulator layer on the substrate, the method comprising:

forming a hard mask layer over the insulator layer;

performing a first patterning process to form a pole and yoke opening in the hard mask layer;

performing a second patterning process comprising forming a photoresist pattern on the hard mask layer, the photoresist pattern exposing the rounded corners of the pole and yoke opening in the hard mask layer, and removing a portion of the hard mask layer exposed by the photoresist pattern to remove the rounded corners of the pole and yoke opening in the hard mask layer;

removing a portion of the insulator layer corresponding to the pole and yoke opening in the hard mask layer to form a trench in the insulator layer; and

filling the trench with a magnetic material.

2. The method of claim **1**, wherein the step of removing the portion of the insulator layer comprises:

performing reactive ion etching on the portion of the insulator layer corresponding to the pole and yoke opening in the hard mask layer.

3. The method of claim **1**, wherein the step of removing the portion of the insulator layer corresponding to the pole and yoke opening in the hard mask layer comprises:

forming a second hard mask layer over the insulator layer prior to forming the first hard mask layer, wherein the first hard mask layer is formed over the second hard mask layer;

transferring the pole and yoke opening from the first hard mask layer to the second hard mask layer; and

removing a portion of the insulator layer exposed by the pole and yoke opening in the second hard mask layer.

4. The method of claim **3**, wherein the step of performing the first patterning process comprises:

forming a photoresist pattern on the second hard mask layer prior to forming the first hard mask layer, wherein the first hard mask layer is formed over the second hard mask layer and the photoresist pattern;

removing a portion of the first hard mask layer along one or more sides of the photoresist pattern; and

lifting off the photoresist pattern from the second hard mask layer.

5. The method of claim **4**, wherein the step of performing the second patterning process comprises:

forming a second photoresist pattern on the first hard mask layer, the second photoresist pattern exposing the rounded corners of the pole and yoke opening in the first hard mask layer; and

removing a portion of the first hard mask exposed by the second photoresist to the remove rounded corners of the pole and yoke opening in the first hard mask layer.

6. The method of claim **1**, wherein the hard mask layer comprises a hard mask material selected from a group consisting of tantalum and ruthenium.

7. The method of claim **1**, wherein the insulator layer comprises alumina.

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